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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	01/31/01	Final, 06/01/96 -- 12/31/00

4. TITLE AND SUBTITLE

Scalable multicast networks for high-performance computing and communications

5. FUNDING NUMBERS

DAAH04-96-1-0234

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

36090-MA-DPS .48

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of this research is to design a class of scalable interconnection networks to support arbitrary multicast communications in highly parallel computing systems. In particular, the project was concentrated on (1) designing routing strategies for multicast networks and developing a network simulator to simulate multicast networks under routing control strategies; (2) deriving necessary and sufficient conditions under which multicast networks are nonblocking; (3) establishing analytical models for the performance of multicast networks; (4) studying self-routing scheme for multicast communication; (5) studying efficient multicast communication in optical networks, and determining rearrangeable and nonblocking conditions in optical multicast networks. (6) studying efficient multicast communication (as well as general collective communication) in both electronic and optical networks. Over the finding period, a number of important results were obtained and these results were reported in 22 journal papers, 1 book chapter, 6 patents (granted or pending), and 30 conference papers. The most important results of this project are summarized in the final progress report and all publications are also listed (attached).

14. SUBJECT TERMS	15. NUMBER OF PAGES 10
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Final Progress Report

Project Title: Scalable Multicast Networks for High-performance Computing and Communications
ARO Award No.: DAAH04-96-1-0234
Principle Investigator: Jianke Yang/Yuanyuan Yang
Institution: University of Vermont/SUNY Stony Brook

The objective of this research is to design a class of scalable interconnection networks to support arbitrary multicast communications in highly parallel computing systems. In particular, the project was concentrated on

- Designing routing control strategies for multicast networks.
- Developing a network simulator to simulate multicast networks under routing control strategies. (2) Deriving necessary and sufficient conditions under which multicast networks are nonblocking.
- Establishing analytical models for the performance of multicast networks.
- Designing low-cost multicast networks.
- Studying efficient multicast communication in optical networks, and determining rearrangeable and nonblocking conditions in optical multicast networks.
- Establishing analytical models for the performance of fault-tolerant networks.
- Studying efficient multicast communication (as well as general collective communication) in both electronic and optical networks,
- Studying self-routing scheme for multicast communication.
- Analyzing rearrangeable and nonblocking conditions in optical multicast switching networks with multicast-capable optical switches.

The most important results of this project are summarized as follows.

- Seven routing control strategies for multicast networks were designed and compared. A multicast network simulator was developed. All seven routing control strategies were implemented on the simulator and evaluated with respect to different measures such as network utilization and blocking probability. Extensive simulations were carried out on the multicast networks for different network size,

workload and traffic distribution, and a large amount of statistical data were collected. The experimental finding is summarized as follows: (1) A network with comparable cost to a permutation network is almost nonblocking for multicast communication. (2) Routing control strategies are effective for reducing blocking probability of multicast networks. The best routing control strategy can provide a factor of 2 to 3 performance improvement over random routing.

- Several analytical models for the performance metrics of multicast networks, such as blocking probability, network throughput, packet transfer time and packet loss probability, were developed and compared. Two types of new multicast networks, restricted multicast networks and self-routing multicast networks, were designed. Both types of multicast networks designed have the same network cost as a permutation network of that type. The first type of network can realize a substantial amount of well-defined multicast connections in a nonblocking fashion. The second type of network can realize arbitrary multicast connections in a rearrangeable, self-routing fashion.

- Efficient multicast communication was studied for a class of WDM optical networks with direct interconnects such as linear arrays, rings, meshes, tori and hypercubes. For each type of the network, necessary and sufficient conditions for the network to be rearrangeably nonblocking and wide-sense nonblocking for multicast connections under several routing algorithms were obtained. An analytical model for the blocking probability of a fault-tolerant Clos network was developed and compared with simulation results, and our results indicate that the Clos network has good fault-tolerant capability.

- Optimal algorithms for multicast and general collective communication were proposed for two types of networks: direct networks and multistage networks in both electronic domain and optical domain. Self-routing multicast networks were designed and self-routing tag encoding schemes were studied.

- Rearrangeable and nonblocking conditions in optical multicast switching networks with multicast-capable optical switches were obtained and new designs for such type of the multicast networks were proposed and compared. A related type collective communication pattern, all-to-all communication was studied. Efficient all-to-all communication algorithms were developed for both direct networks and multistage networks.

Over the funding period, the following research papers/patents have been produced (listed in chronological order).

Refereed Journal Papers

1. Y. Yang and J. Wang, "Optimal all-to-all personalized exchange in a class of optical multistage networks," accepted for publication in *IEEE Transactions on Parallel and Distributed Systems.*

2. J. Wu and Y. Yang, "The postal network: a recursive network for parameterized communication model," accepted for publication in *Journal of Supercomputing.*

3. P. Wan, L. Liu and Y. Yang, "Optimal routing based on super topology in WDM optical parallel interconnects," accepted for publication in *Journal of Parallel and Distributed Computing*, Special Issue on Routing in Computer and Communication Networks.

4. Y. Yang, J. Wang and C. Qiao, "Nonblocking WDM multicast switching networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 11, no. 12, pp. 1274-1287, December 2000.

5. Y. Yang and J. Wang, "A more accurate analytical model on blocking probability of multicast networks," *IEEE Transactions on Communications*, vol 48, no. 11, pp. 1930-1936, November 2000.

6. Y. Yang, "The performance of multicast banyan networks," *Journal of Parallel and Distributed Computing*, vol. 60, no. 8, pp. 909-923, August 2000.

7. P. Wan and Y. Yang, "Load balanced routing in counter-rotated SONET rings," *Networks*, vol. 35(4), pp. 279-286, 2000.

8. Y. Yang and J. Wang, "Optimal all-to-all personalized exchange in self-routable multistage networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 11, no. 3, pp. 261-274, March 2000.

9. Y. Yang, J. Wang and Y. Pan, "Permutation capability of optical multistage interconnection networks," *Journal of Parallel and Distributed Computing*, vol. 60, no. 1, pp. 72-91, Jan. 2000.

10. Y. Yang and J. Wang, "A new self-routing multicast network," *IEEE Transactions on Parallel and Distributed Systems*, vol. 10, no. 12, pp. 1299-1316, December 1999.

11. Y. Yang and G.M. Masson, "The necessary conditions for Clos-type nonblocking multicast networks," *IEEE Transactions on Computers*, vol. 48, no. 11, pp. 1214-1227, November 1999.

12. M.P. Haynos and Y. Yang, "An analytical model on the blocking probability of a fault-tolerant network," *IEEE Transactions on Parallel and Distributed Systems*, special issue on Fault-Tolerant Routing, vol 10, no. 10, pp. 1040-1051, October 1999.

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16. Y. Yang and N.H. Kessler, "Modeling the blocking behavior of Clos networks," *International Journal of Parallel and Distributed Systems and Networks*, vol. 2, no. 1, 1999, pp. 1-9.

17. Y. Yang, "A class of interconnection networks for multicasting," *IEEE Transactions on Computers*, vol. 47, no. 8, August 1998, pp. 899-906.

18. Y. Yang and G.M. Masson, "A fast network controller for nonblocking multicast networks," *International Journal of Parallel and Distributed Systems and Networks*, vol. 1, no. 3, 1998, pp. 149-156.

19. Y. Yang and J. Wang, "On blocking probability of multicast networks," *IEEE Transactions on Communications*, vol. 46, no. 7, July 1998, pp. 957-968.

20. L.A. Calitri and Y. Yang, "Efficient resource placement in generalized de Bruijn networks," *International Journal of Parallel and Distributed Systems and Networks*, vol. 1, no. 3, 1998, pp. 117-126.

21. Y. Yang and L.A. Calitri, "Resource placement in a class of hierarchical networks," *International Journal of Computers and Applications*, vol. 20, no. 1, 1998, pp. 15-25.

22. Y. Yang "An analytical model on network blocking probability," *IEEE Communications Letters*, vol. 1, no. 5, September 1997, pp. 143-145.

Book Chapters

23. Y. Yang, "Supporting Multicast Communication in Clos-Type Switching Networks," in *Switching Networks: Recent Advances*, D.-Z. Du and H.Q. Ngo Eds., Kluwer Academic Publishers, 2000.

Patents

24. Y. Yang and G.M. Masson, "Controller for a Non-Blocking Broadcast Network," United States Patent Number 5,801,641, issued September 1998.

25. Y. Yang and J. Wang, "Self-Router Multicast Network Architecture," United States Patent Application Serial No. 09/049,101, filed March 1998.

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Refereed Conference Papers

30. Y. Yang and J. Wang, "Near-optimal all-to-all broadcast in multidimensional all-port meshes and tori," *Proceedings of 15th IEEE International Parallel and Distributed Processing Symposium (IPDPS 2001)*, San Francisco, CA, April 2001.

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42. Y. Yang (invited), "Nonblocking and almost nonblocking multicast switching networks," *Robust Communication Networks: Interconnection and Survivability*, NSF DIMACS Workshop, Rutgers University, NJ, November 1998, pp. 107-126.

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56. Y. Yang and J. Wang, "Wide-sense nonblocking Clos networks under packing strategy," *Proceedings of the 11th IEEE International Parallel Processing Symposium (IPPS '97)*, Geneva, Switzerland, April 1997, pp. 45-54.

57. L.A. Calitri and Y. Yang, "Resource placement in de Bruijn networks," *Proceedings of the 8th International Conference on Parallel and Distributed Computing and Systems (PDCS '96)*, Chicago, IL, October 1996, pp. 109-116.

58. Y. Yang, "A class of interconnection networks for multicasting," *Proceedings of the 10th IEEE International Parallel Processing Symposium (IPPS '96)*, Honolulu, HI, April 1996, pp. 796-802.

59. Y. Yang and G.M. Masson, "The necessary conditions for Clos-type nonblocking multicast networks," *Proceedings of the 10th IEEE International Parallel Processing Symposium (IPPS '96)*, Honolulu, HI, April 1996, pp. 789-795.

Over the funding period, a number of students have been involved in the research under my supervision and obtained advanceded degrees.

- **Graduate Students Supervised**

- Yang Wang, Master's Degree in Computer Science, May 2000.
  Thesis Title: *Multicasting in a Class of Multicast-Capable WDM Networks.*
  Employment: i2 Technologies, Cambridge, MA.
- Matthew P. Haynos, Master's Degree in Computer Science, May 1998.
  Thesis Title: *An Analytical Model on the Blocking Probability of a Fault-Tolerant Network.*
  Employment: IBM Corporation, Encinitas, CA.
- Chunling Zhou, Master's Degree in Computer Science, Jan. 1998.
  Thesis Title: *Multicast Communication in a Class of WDM Optical Networks.*
  Employment: Sanchez Computer Associates, Inc., Malvern, PA.
- Neil H. Kessler, Master's Degree in Computer Science, May 1997.
  Thesis Title: *Analytical Model for Packing Strategy on Network Blocking Probability.*
  Employment: Thomson Financial Services, Boston, MA.
- Christopher M. Crawford, Master's Degree in Computer Science, March 1997.
  Thesis Title: *Experimental Study of Multicast Routing Strategies.*
  Employment: Sanders, Lockheed Martin, Nashua, NH.
- Lisa A. Calitri, Master's Degree in Computer Science, May 1996.
  Thesis Title: *Resource Placement in Cube-Connected-Cycles and de Bruijn Networks.*
  Employment: Clovis Point, Rochester, VT.
- Michael Landry, Master's Degree, May 1996.
  Comprehensive Exam Title: *Review of Nexus Distributed Operating System.*
  Employment: Lockheed Martin, South Burlington, VT.